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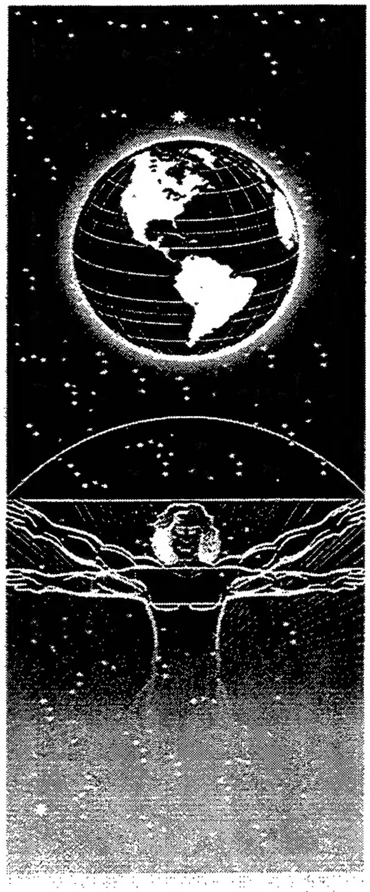

UNITED STATES AIR FORCE RESEARCH LABORATORY

A Comparison of Virtual & Live Human Standing Reach

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This project investigates the ability of virtual human models to simulate human task performance. A variety of reaching tasks were performed by human subjects and their corresponding virtual human using Transom Jack Software. Transom Jack was able to accurately simulate grasping behaviors for approximately 75% of the trials. The most accurate levels were found at waist and acromion (shoulder) heights. There were significant underestimations for reaches at stature (head) height and significant underestimations for reaches at knee height. Conversely, an overestimation of reach can have more serious implications. In nearly half of the trials at knee height, Transom Jack's simulation outreached the human subjects. Nonetheless, virtual humans provide valuable information in many situations and the technology is rapidly improving.

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PREFACE

Recent advances in computer graphics have allowed designers to place simulated humans in solid models of systems for design analyses. These simulated humans, called human figure models (HFMs), are being used for visual and quantitative workspace design and maintenance analysis. There are several commercially available HFMs, each with its own unique characteristics. Design analyses employing these technologies rely on the accuracy of the HFM. This paper describes an evaluation of the Transom Jack™ human figure modeling system for several reaching tasks. The goal of this analysis was to evaluate the accuracy of a HFM compared to a real human. The subjects were anthropometrically measured in order to create their virtual human model. Reaching movements of live subjects and their corresponding human figure models were then compared. The results of this study can be used by analysts using Transom Jack to better understand the strengths and weaknesses of the tool and by system designers to improve the accuracy of Transom Jack, thus increasing the reliability of Transom Jack based design analysis.

The principal investigator for this research was Kristie J. Nemeth, University of Dayton Research Institute, Contract Number SPO900-94-D-0001. This research was conducted under AL/HRGA Work Unit 29400007 - CSERIAC Technology Support.

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INTRODUCTION

The terms *human factors* and *ergonomics* refer to designing for human use (Sanders, and McCormick, 1987). The emphasis is on human beings and how the design of things influences people. A light bulb can have its efficiency evaluated independently of human users, but this is not true of a system like an automobile or aircraft. The human operator is central to systems like these, and system efficiency depends as much on the capabilities of the operator as on the capabilities of the machine.

One goal of a human factors evaluation is to match the capabilities, limitations, and needs of people with the equipment they use. The first step toward this goal is to enhance the effectiveness and efficiency of the activities that are carried out. For example, it is more efficient to arrange components requiring regular maintenance to be clearly visible and easily accessible (Corlett and Clark, 1995). The second step is to enhance certain desirable human values, including improved safety, reduced fatigue and stress, increased comfort, greater user acceptance, increased job satisfaction, and improved quality of life. For example, components should be located to minimize risk of injury during inspection or removal (Corlett and Clark, 1995).

VIRTUAL EVALUATIONS

There are several advantages to integrating human factors evaluations into an engineering design environment. First, appropriately-sized human figures can be shown interacting with models of the equipment or work environment. This allows human factors and engineering analyses to be completed before constructing physical mockups, prototypes, or products (Roebuck, 1995). Second, the results of CAD-based human modeling are easier to understand and communicate because they take advantage of computer visualization. Third, the simulations can be replayed quickly and inexpensively to illustrate the effects of design changes.

DEPTH

Air Force Research Laboratory, Sustainment Logistics Branch (AFRL/HESS) has developed software called Design Evaluation for Personnel, Training, and Human Factors (DEPTH) to help make weapon system designs more conducive to maintenance. DEPTH used (and partially developed) a commercially available 3D virtual human software package called Jack (later named Transom Jack^{TM}).

Using DEPTH, the design analyst can use Computer Aided Design (CAD) data to address maintainability issues such as visibility, reach, accessibility and tool use.

Transom Jack was originally developed at the University of Pennsylvania and later developed and distributed by Transom Technologies. The human model is based on a 31-link, skeletal system with joints including spine fully modeled. Link lengths are defined on the basis of external (surface) dimensions in order to approximate actual bone lengths between adjacent joint centers of rotation (Paquette, 1990).

SAMPLE ANALYSIS

DEPTH was used by Lockheed Martin to evaluate the removal and replacement (R&R) of the F-22 Left-Forward Electronic Warfare Power Supply (LFPS) Line Replaceable Unit. Several ergonomic issues were examined including reach, tool access, visibility, safety and strength. The simulation showed that shorter individuals could not reach the connectors on the far side of the LFPS. For taller individuals, the R&R task required ducking under the outer access panel to gain visual and physical access. After removing the rear signal cables, power cables and locking devices (screws and fasteners), the component was lifted out and set aside. The new unit was then installed by inserting the LFPS into position, replacing the locking devices and connecting the rear cables. The task was to be completed with minimal risk to the maintainer and equipment.

The preliminary test was conducted without the use of expensive prototypes or testing hundreds of potential users. But before the decision-makers on the F-22 program would authorize a redesign of the LFPS, they needed to be convinced that the results of the simulation would be as effective as a physical mock-up evaluation. If the virtual human accurately simulates the size and behaviors of a live human, the company would save significant amounts of time and money. On the other hand, if there are serious discrepancies between the live and virtual humans, the virtual analysis is suspect. At the time, there was insufficient data to back up the validity of virtual human evaluations.

VIRTUAL TECHNOLOGY VALIDATION

This paper addresses a reach analysis of the Transom Jack software under the DEPTH program. The goal of this analysis was to determine how well the model's movements compare to those of a live subjects. While standing, the subjects reached for target objects placed at various heights, distances and orientations and the results were recorded as a series of success and failures. In addition to the reach sessions, the subjects were anthropometrically measured in order to create their virtual human replica –

i.e., their avatar. Once the live subject data was collected and their avatar was created, each reach was simulated in the virtual world. The successes and failures of the avatar were compared to the live human.

Similar work was done by Iavecchia et al (1986) while validating the Crewstation Assessment of Reach (CAR) model. The model is a derivative of the BOEMAN man-model developed by Boeing in 1969 for aircraft cockpit design. It is a non-graphic, interactive program used to determine the percentage of a population that can be accommodated by a particular crewstation layout (Paquette, 1990).

In the CAR study, ten male subjects performed a series of reaches for controls in an F-14 cockpit. The 37 controls used in the study spanned a variety of interactions (clenched, fingertip, and fingertip extended) and areas (right and left side, and vertical side panels, and forward panel). Reaches were performed while the shoulders were restrained in a harness (Zone 1), and also while the upper body was restrained but free to strain against the harness (Zone 2). Across all conditions, CAR correctly predicted Zone 1 reach outcomes in 80% of the cases. The Zone 2 prediction rate was slightly lower at 70%. For Zone 1 and 2 reaches to the side console, the errors were always conservative, predicting failure when success was actual. Likewise, for vertical side reach, 83 of the 85 errors were conservative. For forward reach, however, 10 of the 14 erroneous predictions by CAR of Zone 1 reach, and all of the 33 erroneous predictions in Zone 2 reaches, were successful while failure occurred in the real-world. These were all errors in predicting extended fingertip reaches.

In contrast to the CAR validation, the study reported in this paper examined power-grasp reach in the standing posture rather than seated, precision reach. This felt to be important for maintenance simulations where standing tasks are typical. Due to technology advances in human modeling and simulation, the DEPTH prediction rate was expected to exceed those found in the CAR study.

METHOD

HUMAN DATA COLLECTION

Participants

Twenty male military, civilian, and contractors volunteered from the of the Air Force Research Laboratory (AFRL/HES) at Wright-Patterson Air Force Base, Ohio. Twenty anthropometric measures required by DEPTH were taken for each subject (see Figure 1 for dimension list and Appendix A for subject's data) so volunteers wore clothing that allowed access to body landmarks. The measurement protocol is described in Gordon, et al, 1989. During the reach trials and body measurement, shoes were not worn but socks were allowed.

This study included only males subjects for several reasons. The available pool of subjects was predominantly male, and it would have been difficult to locate a sufficient number of female volunteers, although several females volunteered and were used as pilot subjects. Also, because Transom Jack was initially developed to simulate a male figure, it is presumed that the male figure would be more accurately modeled. The final decision to use only males is primarily due to the differences between male and female body proportions. Size, shape and weight distribution differences may lead to different movement strategies for performing reaches. It is unclear if the male-oriented Transom Jack™ model would reflect these differences.

Acromial Height Standing*	Head Breadth
Biacromial Breadth*	Head Length
Chest Breadth	Hip Breadth Sitting*
Chest Depth*	Knee Height Sitting*
Eye Height Sitting*	Popliteal Height*
Foot Breadth*	Shoulder Elbow Length*
Foot Length*	Stature Sitting*
Forearm-Hand Length*	Stature Standing*
Hand Breadth*	Waist Height OM
Hand Length*	Weight

Figure 1. Dimensions required for virtual human.
**automatic measurement available*

Equipment

The body measuring device included the functions of an anthropometer, beam and spreading caliper. Wooden dowel rods, 2.5 cm diameter and 7.62 cm length, were suspended vertically from posts on a pegboard. Markings were made around the middle of the rods to identify the grasp site. (see Figure 2).

The rods were arranged so that the markings were located at 50, 106, 146 and 176 cm from the ground. These measurements corresponded to the male 50th percentile knee height (lateral femoral epicondyle), waist height (omphalion), shoulder height (acromion height) and stature, respectively (Gordon, et al., 1989). The wooden rods were placed in three locations relative to the sagittal plane: 0° (directly in front), 45° and 90° (to the side). The volunteers stood 40, 60, 80, 100 and 120 cm from the rods.

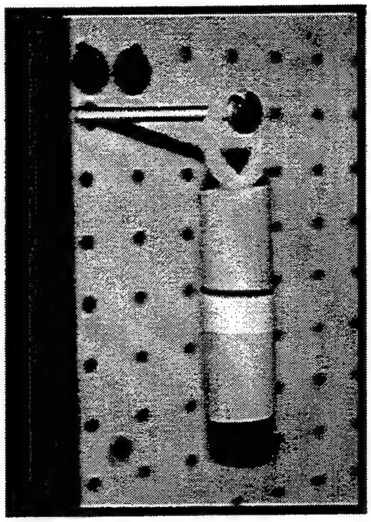

Figure 2. Wooden dowel rod suspended from post on a pegboard. The subject's palm was to contact the dark line in the center of the rod.

Reach Task

Volunteers made contact with the rods using a power grasp. A reach was considered successful when the markings were touched palm-first (see Figure 3), and the rod was removed from the post. Balance had to be maintained throughout the reach with neither foot crossing a tape boundary on the floor.

Four reaches of different constraint types were performed. First the participant reached the peg "using any means possible." This included bending the knees, raising on tip-toes, and lifting one foot off the ground. The second reach was performed with both feet maintaining contact with the floor. Participants could bend their knees, and use tip-toes if necessary as long as a part of both feet stayed on the ground. The third reach allowed hip rotation, but the knees were kept straight and the feet flat on the floor. The fourth reach involved bending the spine without allowing the hips to rotate. Three experimenters observed each subject to assure compliance with the reach constraints.

Due to the unnatural movements required in some reach types, the subjects were allowed to repeat a reach if it was initially unsuccessful. No more than three attempts were made for any grasp condition.

Procedure

After anthropometric data was collected for each subject, the experimenters described the first reaching task. Subjects were able to ask questions at any time throughout the task to clarify requirements. All reaches were completed using the least restrictive reach type before additional constraints were imposed. This was to confirm that natural reaching behavior was measured while at the same time reducing the degree to which subjects mentally analyzed their movements. Within each reach type, subjects attempted the farthest reaches at all heights prior to performing the same set of reaches at shorter distances.

For example, all subjects began by standing at the farthest distance (120 cm), with the rods directly in front (offset 0°). They tried to reach the highest rod (176 cm) using "any means possible." After the experimenters determined if the grasp was a success, subjects reached for the rods at the next highest location (146 cm). They continued reaching for all of the rods directly in front of them using "any means possible." If there was an unsuccessful reach at any of the rod heights, subjects moved to the next closest distance (100 cm). One of the experimenters would prompt subjects to reach for the rod at the height(s) which were previously unsuccessful. Once a successful grasp distance had been determined for each of the rod heights, subjects would rotate their body so that the rods were offset 45° from the sagittal plane. The same procedure was conducted in this direction before subjects rotated so that the rods were located

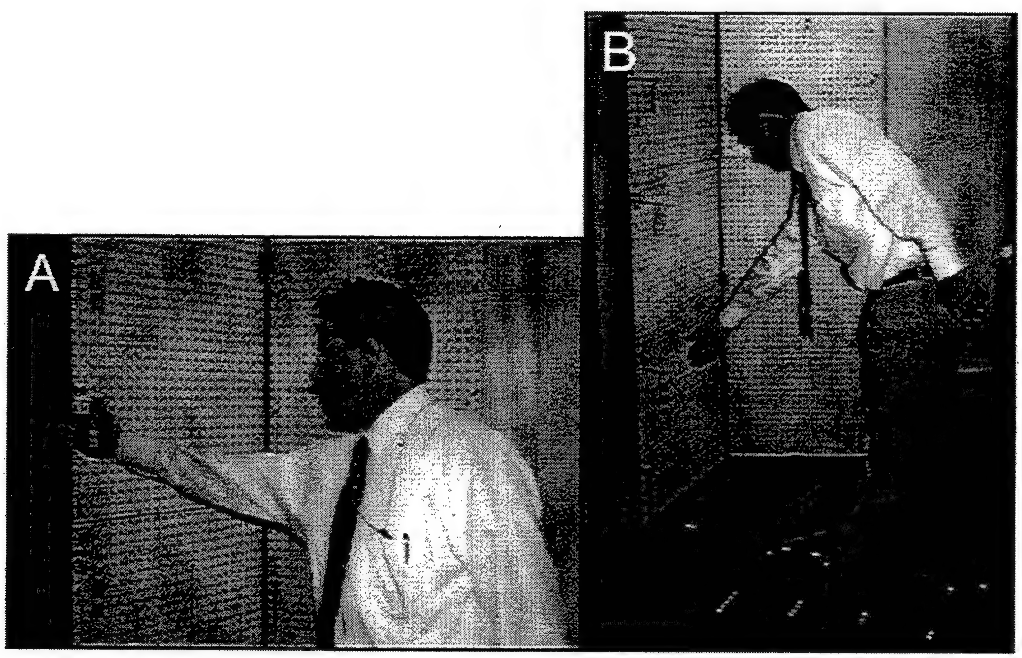

Figure 3. (A) Grasp was acceptable when palm makes contact with rod-target and subject maintains balance. (B) Subject was unable to contact target when bending only the spine.

to the side (90° from the sagittal plane). The complete process was repeated for each type of reach (knee bending, hip bending, and spine bending).

DEPTH DATA COLLECTION

A virtual environment was created in DEPTH to represent the physical mockup. Sites were placed at each target location. The same dataset of subjects was used as in the first phase. See Figure 4 for an example of a subject in the virtual environment.

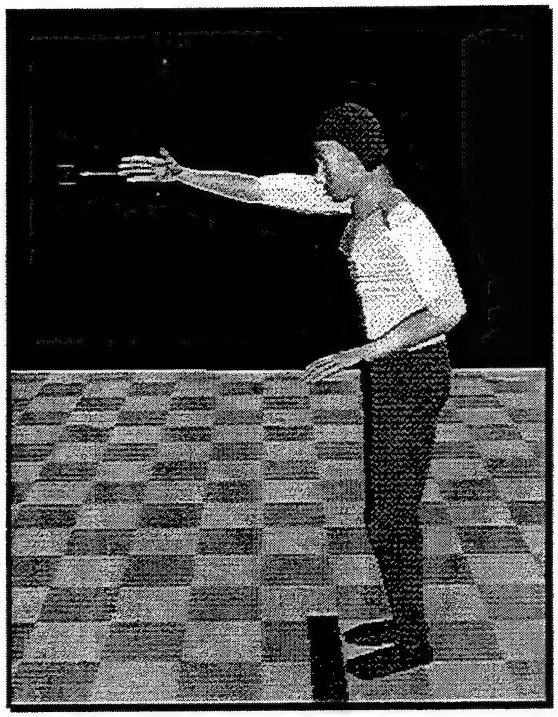

Figure 4. The human shown in figure 3 is depicted as a virtual model in DEPTH.

After inserting the virtual model of each subject into the environment, it was moved to a location on the floor so that both feet were behind the tape lines. This procedure is similar to how the humans lined-up in front of the pegboard. Transom Jack's *Human Behaviors* option was turned on so that the model would maintain balance. Because the model cannot balance on one foot, and is difficult to control when the knees are bent, it was only possible to simulate the two most restrictive reach types (spine and hip bending).

Command-line codes were used to manipulate Transom Jack™ directly. A grasp was successful when the model's palm made contact with the peg site. To simulate spine bending without hip rotation, the *Move Arm*, and *Move Center Of Mass* commands were implemented using three different procedures. First, the reaching ability of the model was determined when the hand was snapped to the grasp site using the *Move Arm* command (using the right hand, starting from the palm and rotating from the waist). The next series of reaches started by snapping the hand to the grasp site, but the hand was also manually adjusted using the mouse to confirm that the model had reached its reach limits. In the final series, the center of mass was first shifted over the toes of the model to simulate the way humans shift their weight during long reaches. The arm was then snapped and stretched to the grasp site.

DEPTH data collection for the next reach type (bending at the waist),was conducted similarly, except that the model's pelvis was first rotated forward to direct the upper body toward the target site (the *Rotate Pelvis* command was used). The same three procedures as used above were employed in order to determine the level of manual control of the model required to accurately simulate human reaching behavior.

On several reach attempts, the model's upper torso was in an awkward posture which limited its reach. In these cases, the model was re-inserted into the original standing posture and the reach was repeated. Manual manipulation of the model allowed posture changes to maximize reach capability.

RESULTS

The farthest distance for a completed grasp was determined for both the live and virtual humans. When the distances matched, the outcome was considered "accurate." The alternative outcomes were under- or over-estimating the humans' reach abilities. In some cases, neither the live nor virtual human was able to complete a grasp at even the closest distance.

The data reviewed in this section were collected in DEPTH using the most manually intensive procedures. This includes moving the center of mass, and manually adjusting the arm. These procedures achieved the highest accuracy ratings. The comparisons between each DEPTH reach procedure and the corresponding human reach are presented in Appendix B.

The first step in the analysis was to compare the numbers of accurate and inaccurate judgments. Overall, there were no differences in the percent of accurate judgments made for Spine ($\underline{M}$=64%) or Hip Bending ($\underline{M}$=46%) reaches, $t(11)=1.808$, $p=.098$. There were also no differences found between Spine ($\underline{M}$=17%) and Hip bending ($\underline{M}$=4%) in the percent of overestimated reaches, $t(11)=1.835$, $p=.094$. There was a significantly greater percentage of underestimations found for Hip Bending ($\underline{M}$=48%) over Spine Bending ($\underline{M}$=19%), $t(11)=-2.73$, $p=.019$ (see Figure 5).

Figure 6 allows a better examination of how the judgments fared at each rod height and reach direction. When the task involved bending the spine only, the accuracy of the virtual model to predict human reach ability ranged, for the most part, from 55% to 75% (A). When reaching to the side for the lowest target, the virtual model accurately predicted reach capabilities for 20% of the subjects. In this condition, the virtual model overestimated reach capabilities for 80% of the subjects (C). For the other rod heights and reach directions, there were an equal number of over and underestimations (C&E).

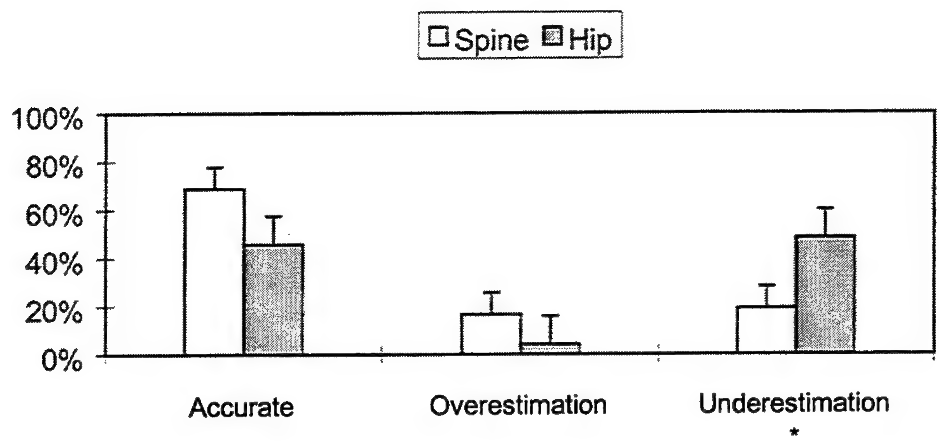

Figure 5. Judgment outcomes for Spine and Hip Bending type reaches.
*Note: *=significant at alpha =.05*

The accuracy of the hip bending reach varied from 5% up to 90% (B). It is clear from the figure that for this reach type, the virtual model was more accurate when the target was directly in front of the subjects, or at the highest target location. There were relatively few overestimations, but a large number of underestimations when the target was either offset 45° or 90° (D&F).

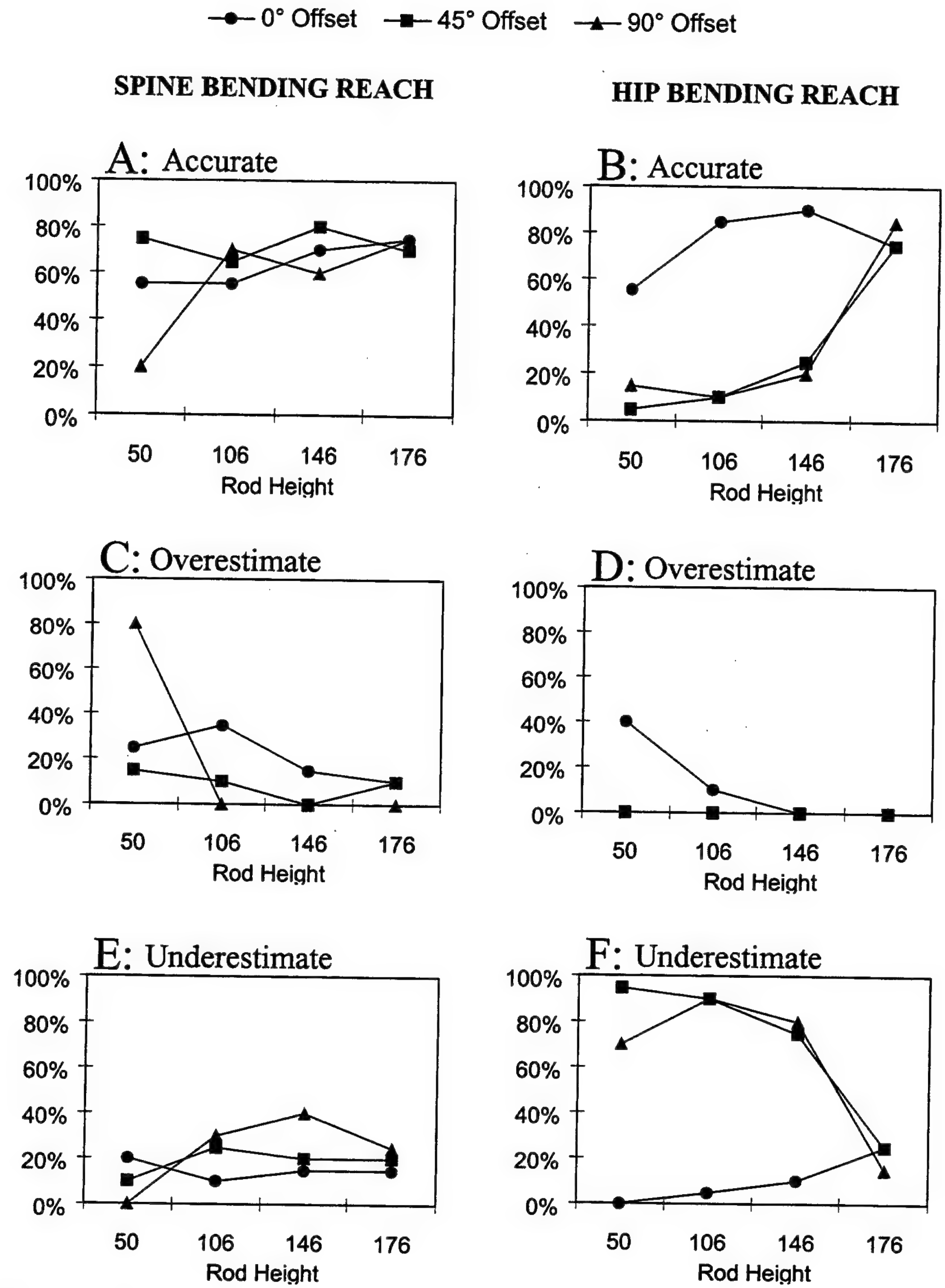

Figure 6. Ability of the virtual model to simulate reach tasks performed by a live human.

DISCUSSION

The accuracy of the virtual model to predict human reach capability was lower than expected. Although the CAR model was found to be 70-80% accurate (Iavecchia et al, 1986), the virtual model in the current study was, on average, 46-64% accurate. For the range of rod heights and reach directions, the virtual model was more accurate when there were greater constraints on the type of reach. As the reaching behavior became more natural (involving more body parts), the model was less accurate.

Of course, allowing the hips to bend increases the degrees of freedom that can be used to complete the task. In the first set of reaches in the CAR validation, only the arm was free to move because the torso was restrained in a harness. The virtual model had to simulate only the hand, lower and upper arm placement of the human. The spine bending reach employed here required the virtual model to predict the hand, lower and upper arm, shoulder/clavicle, and torso placement of the human. Certainly this poses a greater challenge.

Research has shown that human movement with multiple degrees of freedom is not easily described. Mark, et. al. (1997) found that subjects moved their torso forward when reaching for an object placed within the reach of their arm. Although the torso movement was not necessary, subjects seemed to use a functional reach boundary instead of the theoretical boundary indicated by the length of their arms.

Research on balance shows similar findings: Holbein and Chaffin (1997) found that people often do not or cannot reach their theoretical stability limit. To maintain balance, a subject's center of gravity (COG) must stay within the base of support (e.g., the outer edge of the feet while standing). The theoretical stability limit is the same as the base of support. Holbein and Chaffin found that subjects restricted their COG movements within a functional limit which was well within the theoretical limit.

When human movement relies on functional limits instead of theoretical limits, creating a virtual model is more difficult. Individual differences also contribute to prediction error. A comparison between subjects of similar sizes would still find differences in reaching ability. One person may be more flexible, or shift their weight more efficiently. It was these expected differences between people which makes an analysis of the specific motion pathways for each body part almost impossible (Hale, et al. 1997). Subject A might reach for the target with the shoulder adducted (elbow raised to the side), while subject B reaches by flexing the shoulder (elbow raised to the front). If both of these subjects are able to safely perform the task, then their body positioning is initially of less importance. It was for this reason that the

current study focused on the accuracy of the virtual model to predict reach judgments, instead of examining the body postures and techniques used to complete the task.

The high level of prediction errors that occurred should be interpreted cautiously because reach ability was measured in intervals of 20 cm. It is possible that the virtual human was able to reach a specific target, while the corresponding human may have missed the target by only 2 cm. It is also possible that the discrepancy could have been as large as 19 cm. If a more precise measure of maximum reach is desired, the distance intervals must be decreased. New studies should focus on both reach judgments (whether or not the target could be reached) and miss distances, as done by Iavecchia, et al., (1986). Miss distance is a measure of the distance that a control would have to be moved toward the operator (or, conversely, the operator moved toward the control) in order to enable the operator to operate the control. This would help to quantify the judgment errors which occurred.

A second quantification problem, addressed in an earlier study (Nemeth, 1997), should also be considered. Differences were found between the values used as inputs in the model-generation procedure and the size of the resulting figure. For example, the virtual models had shoulder breadth measurements that were an average of 3.7 cm larger than the shoulder breadth of the corresponding human. Shoulder height was overestimated by an average of 1.87 cm, while shoulder-elbow length was underestimated by 1.5 cm (Note: these values were replicated with the current subject sample).

Carrier et al., (1998) have suggested that while $^{+/-}$1 cm is often required, software featuring an articulated human model should strive for body surfaces with an accuracy of $^{+/-}$0.3 to 0.4 cm.. Yanagida (1995) also argued for tight tolerances by stating that the size of the virtual human should exactly replicate that of the real operator. Hand size, arm length, and eye placement should be set identical to the real operator. If discrepancies are allowed (e.g., in arm length or interpupillary distance), the perception of distance to the hand and target object may be skewed. Although a specific segment's tolerance will depend on it's relevance to the task, future work should investigate the source of error in these measurements.

CONCLUSION

Graphical tools for human factors analysis are clearly the future for design evaluations. We are still learning how to accurately represent human size, shape, and motion. As we continue to learn how to incorporate this information into graphical programs, human modeling tools should become even more

valuable. Additional research which serves to quantify and predict human motion will allow for greater accuracy in virtual technology.

Although there are many individual differences between people when performing a reaching task (e.g., muscle stiffness, joint flexibility), DEPTH using the Transom Jack™ model should be adequate for a preliminary evaluation of a workspace. When a more detailed analysis is necessary, physical mockups using human test-subjects may be required. Subsequent versions of Transom Jack are expected to improve its accuracy.

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ACRONYMS

AFRL	Air Force Research Laboratory
CAD	Computer Aided Design
CAR	Crewstation Assessment of Reach
COG	Center of Gravity
DEPTH	Design Evaluation for Personnel, Training, and Human Factors
HESS	Human Effectiveness Directorate, Deployment and Sustainment Division, Sustainment Logistics Branch
HFMs	Human Figure Models
LFPS	Left-Forward Electronic Warfare Power Supply
R&R	Removal and Replacement

APPENDIX A

Table A-1 Anthropometric data collected from participants used to create a virtual model.

Subject	Stature	Acromion Ht	Waist Ht	Hand Lgth	Head Brdth	Shoulder Brdth	Chest Brdth	Hip Brdth	Foot Brdth	Sitting Height	Eye Ht Sitting	Shoulder Elbow Lgth	Popliteal Ht	Hand Brdth	Knee Ht Sitting	Head Lgth	Chest Dpth	Elbow Fingertip Lgth	Foot Lgth	Weight
1	178.6	147.8	107.0	19.5	15.2	38.1	26.9	31.5	9.7	91.6	79.8	32.4	43.9	8.6	54.4	19.4	20.9	42.5	22.0	179.3
2	180.2	150.1	109.9	18.5	15.0	40.3	37.6	38.6	9.8	89.9	76.9	37.6	44.1	8.8	53.2	20.9	29.9	47.8	26.9	226.0
3	170.2	140.9	101.5	17.8	14.6	35.0	31.8	33.0	10.0	91.8	80.3	35.7	43.0	8.2	51.9	19.8	23.2	45.7	27.6	160.0
4	175.1	145.0	103.8	19.3	14.0	38.2	35.4	35.8	9.8	92.9	79.1	34.7	43.1	8.9	54.4	19.8	26.6	46.0	26.9	180.0
5	171.6	141.3	103.1	18.9	14.9	36.2	31.4	33.7	9.5	87.8	74.2	35.4	45.5	8.5	55.1	19.4	21.8	45.1	25.2	145.0
6	176.5	148.2	107.3	19.2	14.5	36.2	30.9	33.6	9.4	92.8	79.0	38.1	44.0	8.2	52.9	19.1	20.8	48.6	27.5	155.0
7	189.1	157.4	116.0	20.6	15.2	44.1	32.8	35.8	10.6	99.2	85.8	37.7	46.6	9.4	57.6	20.1	23.1	51.2	29.1	198.0
8	182.6	148.8	109.5	20.0	15.8	39.0	36.3	40.6	10.5	94.9	78.5	36.9	43.2	8.5	55.8	21.0	25.8	48.8	27.4	215.0
9	175.9	144.8	108.1	20.5	14.9	34.7	31.8	35.1	9.7	89.0	77.1	36.2	44.1	8.6	54.9	21.2	24.2	49.0	26.9	170.0
10	182.8	148.3	105.3	21.8	15.8	39.7	31.8	39.1	10.1	91.6	78.7	36.2	43.2	9.2	53.8	20.9	27.5	49.6	26.6	234.1
11	175.5	147.2	106.7	19.3	14.9	42.8	32.7	34.4	10.4	88.2	78.9	37.6	42.6	9.1	54.0	19.1	24.7	47.9	26.4	170.0
12	170.5	139.3	105.6	18.2	15.2	35.8	29.0	35.2	10.3	88.3	77.6	34.9	46.1	9.0	55.0	20.5	22.7	47.8	25.9	150.0
13	171.0	139.3	103.5	16.7	15.0	38.0	32.3	35.3	10.0	88.2	77.1	34.0	40.4	8.8	51.4	19.7	19.5	46.1	25.6	155.0
14	183.5	153.2	114.8	20.9	15.3	42.9	36.5	36.8	11.4	93.2	81.2	40.4	49.7	8.6	58.4	21.2	26.5	52.5	28.6	215.0
15	178.1	145.1	106.8	17.6	14.8	35.6	28.3	32.5	9.5	93.4	83.2	35.9	43.8	8.6	53.7	20.5	21.9	46.4	24.2	134.0
16	177.3	144.7	106.4	20.0	16.2	42.3	38.3	39.0	10.6	93.7	81.0	36.8	45.3	8.4	55.7	21.0	27.5	47.5	27.7	215.0
17	173.3	142.8	103.0	19.7	15.8	42.4	38.2	39.0	10.6	90.3	79.9	36.6	44.8	8.3	55.7	20.5	28.6	47.2	27.6	220.0
18	170.6	149.1	107.2	18.5	16.8	37.5	33.1	35.6	9.7	93.1	82.3	37.9	44.6	8.3	53.2	19.2	23.6	45.7	26.8	162.0
19	168.9	138.3	102.5	17.7	15.4	40.7	33.5	35.5	10.3	90.9	80.6	34.0	43.8	8.5	51.6	20.1	24.7	45.4	25.3	175.0
20	168.5	141.5	101.0	18.8	16.4	37.1	41.2	37.4	10.1	88.9	77.3	33.8	40.2	8.1	50.3	19.3	30.5	46.8	25.6	210.0

APPENDIX B

Table B-1. Comparison of DEPTH reach judgment with human ability for Spine Bending task

0 offset

Snap Only				Snap, & Stretch				Snap, Stretch & Move CM			
	Outcomes				Outcomes				Outcomes		
Rod Height	Underestimate	Overestimate	Accurate	Rod Height	Underestimate	Overestimate	Accurate	Rod Height	Underestimate	Overestimate	Accurate
176 cm	100%	0%	0%	176 cm	30%	10%	60%	176 cm	15%	10%	75%
146 cm	100%	0%	0%	146 cm	35%	10%	55%	146 cm	15%	15%	70%
106 cm	95%	0%	5%	106 cm	35%	15%	50%	106 cm	10%	35%	55%
50 cm	20%	0%	80%	50 cm	20%	0%	80%	50 cm	20%	25%	55%

45 offset

Snap Only				Snap, & Stretch				Snap, Stretch & Move CM			
	Outcomes				Outcomes				Outcomes		
Rod Height	Underestimate	Overestimate	Accurate	Rod Height	Underestimate	Overestimate	Accurate	Rod Height	Underestimate	Overestimate	Accurate
176 cm	100%	0%	0%	176 cm	100%	0%	0%	176 cm	20%	10%	70%
146 cm	100%	0%	0%	146 cm	100%	0%	0%	146 cm	20%	0%	80%
106 cm	100%	0%	0%	106 cm	95%	0%	5%	106 cm	25%	10%	65%
50 cm	10%	0%	90%	50 cm	10%	0%	90%	50 cm	10%	15%	75%

90 offset

Snap Only				Snap, & Stretch				Snap, Stretch & Move CM			
	Outcomes				Outcomes				Outcomes		
Rod Height	Underestimate	Overestimate	Accurate	Rod Height	Underestimate	Overestimate	Accurate	Rod Height	Underestimate	Overestimate	Accurate
176 cm	90%	0%	10%	176 cm	90%	0%	10%	176 cm	25%	0%	75%
146 cm	90%	0%	10%	146 cm	80%	0%	20%	146 cm	40%	0%	60%
106 cm	85%	0%	15%	106 cm	55%	0%	45%	106 cm	30%	0%	70%
50 cm	5%	0%	95%	50 cm	5%	0%	95%	50 cm	0%	80%	20%

Table B-2. Comparison of DEPTH reach judgment with human ability for Hip Bending task.

0 offset

Snap Only

Rod Height	Underestimate	Overestimate	Accurate
176 cm	100%	0%	0%
146 cm	100%	0%	0%
106 cm	95%	0%	5%
50 cm	65%	5%	30%

Snap, & Stretch

Rod Height	Underestimate	Overestimate	Accurate
176 cm	100%	0%	0%
146 cm	95%	0%	5%
106 cm	95%	0%	5%
50 cm	60%	10%	30%

Snap, Stretch & Move CM

Rod Height	Underestimate	Overestimate	Accurate
176 cm	40%	0%	60%
146 cm	0%	0%	100%
106 cm	5%	10%	85%
50 cm	0%	45%	55%

45 offset

Snap Only

Rod Height	Underestimate	Overestimate	Accurate
176 cm	95%	0%	5%
146 cm	100%	0%	0%
106 cm	100%	0%	0%
50 cm	95%	0%	5%

Snap, & Stretch

Rod Height	Underestimate	Overestimate	Accurate
176 cm	95%	0%	5%
146 cm	100%	0%	0%
106 cm	95%	0%	5%
50 cm	95%	0%	5%

Snap, Stretch & Move CM

Rod Height	Underestimate	Overestimate	Accurate
176 cm	40%	0%	60%
146 cm	85%	0%	15%
106 cm	95%	0%	5%
50 cm	95%	0%	5%

90 offset

Snap Only

Rod Height	Underestimate	Overestimate	Accurate
176 cm	100%	0%	0%
146 cm	100%	0%	0%
106 cm	100%	0%	0%
50 cm	95%	0%	5%

Snap, & Stretch

Rod Height	Underestimate	Overestimate	Accurate
176 cm	100%	0%	0%
146 cm	100%	0%	0%
106 cm	100%	0%	0%
50 cm	95%	0%	5%

Snap, Stretch & Move CM

Rod Height	Underestimate	Overestimate	Accurate
176 cm	30%	0%	70%
146 cm	90%	0%	10%
106 cm	90%	0%	10%
50 cm	85%	0%	15%